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# **Comparative cradle-to-gate life cycle assessment of wood pellet production with torrefaction**

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## **Abstract**

Torrefaction is a thermal pre-treatment process for upgrading raw biomass into a more energy dense fuel. Torrefied biomass is combined with a densification process to increase its bulk density similar to conventional wood-pelleting production. This paper identifies the significant environmental impacts associated with production and delivery of these two fuels, using cradle-to-gate life cycle assessment. A feedstock of Scots Pine is modelled for a localised torrefaction/wood pellet plant located in Norway, with the products from each facility delivered to a power station in the UK.

Results show that the relative benefits of torrefaction over wood-pellets are higher on per MJ delivered basis due to the higher calorific value of the fuel. The climate change and fossil depletion impacts for torrefied pellets modelled were lower than wood pellets, using an assumption that the drying requirement of the reactor was 3.0MJ/kg water removed for both cases. Sensitivity analysis of the model indicated that the relative impact improvement of the torrefied pellet case compared to wood pellets is strongly dependent on the biomass drying requirement and the proportion of total process heat supplied by the re-circulated torrefaction gas. Land requirements for torrefied pellets are higher due to the mass losses in production.

## **Highlights**

- **Life Cycle Assessment performed to assess torrefaction in wood pellet production**
- **Comparative LCA of wood pellet production with and without torrefaction stage**
- **Torgas recirculation allows for reduced demand for external utility fuel supply**
- **Torrefied pellets offer energy and greenhouse gas savings but increase land use**
- **Results are sensitive to assumptions on energy required for drying and torgas use**

**Keywords:** Life cycle assessment; torrefaction; wood pellets; LCA; bioenergy; torrefied pellets

## **1. Introduction**

EU countries are required to increase the use of renewable energy and reduce greenhouse gas emissions by 2020 and beyond [1, 2]. Bioenergy is increasingly utilised to contribute towards these multiple policy objectives, however the local supply is often very limited due to insufficient land availability, which has led to a rapid increase in biomass imports to the EU [3]. Biomass is unique as a renewable resource, being a carbon carrier capable of storage and on-demand use making it an attractive energy source [4]. There are however several challenges associated with raw biomass which include variability, high moisture content (MC), low calorific value (CV), low bulk density, and issues around bulk handling, transportation, and logistics [5, 6]. Torrefaction may address these

problems to produce a more homogeneous fuel with an increased energy density and lower MC thereby improving supply chains [7-9]. It is suggested that torrefaction with densification is preferable due to improved bulk density and wider handling and transport benefits [4].

Presently wood pellets are the preferred form of biomass for transport and handling over long distances with supply rapidly increasing over the last decade [3]. Future demand for wood pellets is anticipated to continue expanding due to Government support for bioenergy in the UK and EU [6]. The environmental burdens of conventional wood pellet supply are reasonably well understood from previous research and due to biomass sustainability criteria [10-12]. In contrast there have only been limited studies which attempt to evaluate the environmental effects of torrefied wood pellets [11, 13, 14]. This paper addresses some of the existing research gaps by performing a life cycle assessment (LCA) of torrefied wood pellets (TP) and comparing the results with conventional wood pellet production (WP).

### **1.1. Characteristics of torrefaction**

Torrefaction is a thermal treatment method for the conversion of biomass carried out within a relatively low temperature range of 200-300°C, at atmospheric pressure in the absence of oxygen. This pre-treatment step destructs the fibrous structure and tenacity of biomass [7]. After torrefaction biomass exhibits hydrophobic characteristics making storage of torrefied biomass more attractive and less susceptible to biological degradation [5]. During the torrefaction process inherent moisture within the biomass is driven from the product. This drying occurs alongside a corresponding solid mass loss, achieved through the partial devolatilisation of the biomass' lignocellulosic structure. The initial energy content within the lignocellulosic structure is mainly preserved in the solid product, due to only limited devolatilisation in the relatively low reaction temperature range. This results in a product energy density higher than the original biomass, thus producing an energy carrier with an increased calorific value (CV). A typical mass and energy balance for woody biomass torrefaction is that 70% of the mass is retained as a solid product, containing 90% of the initial energy content [15]. The other 30% of the mass is converted into torrefaction gas (known as 'torgas'), which contains only 10% of the energy of the biomass. Torgas can be utilised as a beneficial energy source (utility fuel) in torrefaction in order to improve the overall process efficiency [9, 16].

Torrefaction is able to convert biomass feedstock with non-uniform qualities into a highly homogenous bioenergy material. It assists post-production applications as a pre-conditioning process, eliminating the need for energy conversion systems to include inefficient and expensive methods to handle feedstock variability (e.g. specialist size reduction equipment required for pulverising WP in co-firing coal plants). This is crucial as issues concerning feedstock handling and transfer are often quoted as the biggest obstacles to effective conversion and use of biomass feedstock [5]. The added value compared to wood pellets includes higher co-firing percentages, cost savings in handling and transport, reduced sensitivity to degradation, and improved milling properties [4, 7, 8, 15]. Table 1 outlines the product characteristics of torrefied woody biomass and TP compared to coal, WP and raw biomass, revealing that TP have features, like handling, milling, and transport requirements, similar to coal [8, 9]. The table also demonstrates why torrefaction with densification (e.g. pelletisation) is required to realise any potential logistical advantages.

**Table 1: Indicative physical properties of different biomass fuels and coal [5, 8, 9, 17]**

Parameter	Wood Chips	Wood Pellets (WP)	Torrefied Wood	Torrefied Pellets (TP)	Coal
Moisture content (MC) (wt.%)	30-50	7-10	3	1-5	10-15
Lower Calorific Value (CV) (MJ/kg)	9-12	15-16	19-23	20-24	23-28
Bulk Density (kg/m <sup>3</sup> )	250-300	550-700	180-300	750-850	800-850
Grindability (kWh/t)	237	237	23-78	23-78	12
Hygroscopic nature	Hydrophilic	Hydrophilic	Hydrophobic	Hydrophobic	Hydrophobic
Biological Degradation	Yes	Yes	No	No	No
Milling Requirements	Special	Special	Classic	Classic	Classic

## 1.2. Aims and Objectives of the study

The primary aim of the study is to assess the environmental impacts associated with integrating the torrefaction process into the bioenergy supply chain. This aim can be summarised as:

“Complete an environmental LCA of the torrefaction with pelletisation and wood pellet bioenergy chains on a cradle-to-gate basis with a functional unit of 1 ton or 1MJ of TP/WP delivered”.

An initial LCA was performed to evaluate the TP production process which used several modelling assumptions. A comparison of TP against the current WP technology [5] was then conducted to give context to the results of the LCA study and complete the comparative LCA between TP and WP.

Specific objectives of the study were:

- Compile a detailed life cycle inventory (LCI) of the TP/WP process chains
- Complete a cradle-to-gate LCA of the TP/WP bioenergy chains
- Perform an impact assessment and compare the results of the TP/WP process
- Perform sensitivity analysis to evaluate the significance of the following key modelling assumptions:
  - A. Drying energy requirement to remove 1kg water from biomass (3.0, 6.0 and 9.0 MJ/kg removed) including consideration of the CV of torgas
  - B. Post treatment grinding energy requirements of the TP process compared to the WP case
  - C. Post treatment pelleting energy requirements of the TP process compared to the WP case
  - D. Delivery requirements for increased and decreased transportation distances.

## 2. Methodology

### 2.1. Environmental Life Cycle Assessment

Life Cycle Assessment (LCA) studies the potential environmental impacts throughout a product's or system's life from raw material acquisition through production, use and disposal [18-20]. The general purpose of LCA is to provide a holistic view of the emissions and resource requirements of a product system. Impacts of activities involved in the extraction, refining, transport and use of the materials and fuels are considered. When applied to torrefied wood pellet production the activities considered include biomass cultivation and collection, transportation, size reduction and screening, drying, torrefaction, pelletisation, storage, and distribution of TP/WP to the end-user. The

comprehensive view provided by LCA allows environmental impacts to be assessed on a whole system basis.

There are four main stages in the LCA process: i) goal and scope definition, ii) life cycle inventory (LCI), iii) impact and improvement assessment, and iv) interpretation [18, 19]. This LCA was performed using SimaPro 7.3 software [21] and the database ecoinvent 2.0 [22] for background data. This software enables the manipulation and examination of inventory data in accordance with the LCA ISO Standards. Other data has been collected from a variety of sources as described in the inventory (see section 3).

## **2.2. Goal and scope definition**

The goal of the LCA study is consistent with the aims and objectives outlined in section 1.2. This can broadly be defined as 'compare the environmental impacts of the TP/WP bioenergy chains and identify which component processes contribute most to the overall impact score in each case'. The scope considers impacts from the major processes in the TP/WP bioenergy chains only, as described in section 3. Some auxiliary processes (e.g. cleaning and maintenance) together with waste and disposal protocols are excluded from the study. The use phase (i.e. combustion of TP/WP) is not included as the system boundary ends at the delivery of the pelleted fuel to the end-user, e.g. a power plant for co-firing.

System boundary description determines which unit processes are included within the LCA study. The system boundary described in section 3 can be summarised as follows:

- Cradle-to gate (biomass production through to delivery of TP/WP to end user) inventory
- Include material requirements of pre-processing, processing and delivery equipment and storage units
- Exclude material requirements of planting, growth and cultivating equipment
- All energy requirements (fuels and electricity) are included along with other operational inputs including farming/forestry inputs, transportation, processing, and distribution.

The primary function of the system is the production of torrefied wood pellets (TP) or conventional wood pellets (WP) for use in bioenergy production systems. As described in the aims and objectives (see section 1.2) the functional unit is defined as 1 ton or 1 MJ (of TP/WP) fuel delivered. Both functional units are used in the results section to analyse and assess the varying facets of the bioenergy supply chains considered.

## **2.3. Life Cycle Inventory**

The main purpose of the Life Cycle Inventory (LCI) is to identify and quantify the energy, water and materials usage and environmental releases (e.g. air emissions, solid waste disposal, and wastewater discharges). LCI analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. The data collection focuses on the operational inputs and outputs (e.g. fuel and electricity use and associated resource use and emissions), and materials and equipment consumed to manufacture, construct, and operate the wood pellet production facility. The calculation procedures involve obtaining relevant data for each inventory item, which together are compiled to produce the LCI for the functional unit. Water use and wastewater are excluded

from this LCI due to insufficient data available. The LCI for this paper is further described in the system description and modelling assumptions (see section 3).

## **2.4. Life Cycle Impact Assessment**

In the life cycle impact assessment (LCIA) stage, an assessment is made of the potential human, ecological, and depletion effects of energy, water, and material usage; and the environmental releases identified in the inventory. The impact assessment is where the potential effects on the chosen environmental issues are assessed [20]. This stage is further subdivided into three elements: classification, characterisation, and normalisation [18, 19]. The LCIA attempts to establish a linkage between the product or process and its potential environmental impacts. In this study, results are characterised and normalised using ReCiPe impact assessment methodology [23], using the same approach as in a previous LCA of biomass gasification [20].

Results are analysed using the midpoint categories, as these indicators are chosen closer to the inventory result and hence have a lower uncertainty. Midpoint results are also easier to interpret from an engineering and scientific perspective, and provide additional use for comparison to other LCA and energy system assessments [11-14]. A total of 18 impact categories were assessed using ReCiPe [23] however some categories have been omitted from the displayed results as they were found to have very negligible effects. Water depletion was also excluded due to insufficient LCI data. An initial assessment of the relative importance of environmental issues was performed by normalising the characterised data using ReCiPe endpoint, using a consistent approach with previous studies [20].

Environmental issues considered in the study include effects on human health (e.g. toxicity, particulates); ecosystems (e.g. acidification, eutrophication); land use; resource (mineral and fossil) depletion; energy usage; and climate change. Environmental burdens relating to the processing and storage of wood, dust from wood chipping, local air quality, leaching, and biodiversity impacts are not included in the study. Most of these are not usually included in an LCA as they are more localised impacts and difficult to quantify on a wider scale [18-23].

## **2.5. Interpretation**

Interpretation is the final stage of the LCA but is crucial in assessing the study's accuracy, uncertainty, limitations, and whether the goal and scope is achieved. When interpreting results a sensitivity analysis is performed to evaluate the significance of the principal modelling assumptions. The sensitivity cases A to D (outlined in section 1.2) are presented in the Results (see section 4), with additional interpretation provided in the Discussion (see section 5).

## **2.6. Net Energy Analysis**

Net energy analysis is a methodology whereby the energy required to manufacture a good, or create a service may be computed [24]. It takes into account both direct and indirect energy use and calculates the gross energy requirement (GER) [24, 25]. To determine the primary energy inputs needed to produce a given amount of product or service, it is necessary to trace the flow of energy through the relevant industrial system. The system boundary for this net energy analysis is the same as used in the LCA. Data obtained in the LCI is therefore adequate to perform the net energy analysis. To calculate the GER for the facility construction and lifetime operation, the life cycle

impact assessment method (LCIAM) Cumulative Energy Demand (CED) [26] was applied to the LCI. This LCIAM expresses results in terms MJ, valued as primary energy during the complete life cycle of the TP/WP systems.

### 3. System Definition and Modelling Assumptions

In performing a LCA it is essential to address the requirements of the goal and scope definition and life cycle inventory (LCI) as described in sections 2.2 & 2.3. This section therefore defines the torrefied wood pellet system and assumptions required to develop the LCA model. In the inventory stage, data collection was performed using practical data gathering, literature searches, and through the use of software. A description of the main aspects of the LCI is presented here with additional supporting information provided in the supplementary data.

#### 3.1. Torrefaction Plant Overview

This study focuses on a generic torrefaction plant with the model chosen to represent this based on a directly heated reactor, incorporating an integrated torgas recovery system, similar to the plant design developed by ECN [8, 15, 27]. The basic layout of the combined torrefaction and pelleting plant is shown in Figure 1. Portrayed are the major and ancillary processes of the torrefaction plant as well as the expected inputs and emissions to and from the system. Further description of the torrefaction plant and process is described in the sub-sections below, in addition to the similarities and differences with conventional wood pellet production.

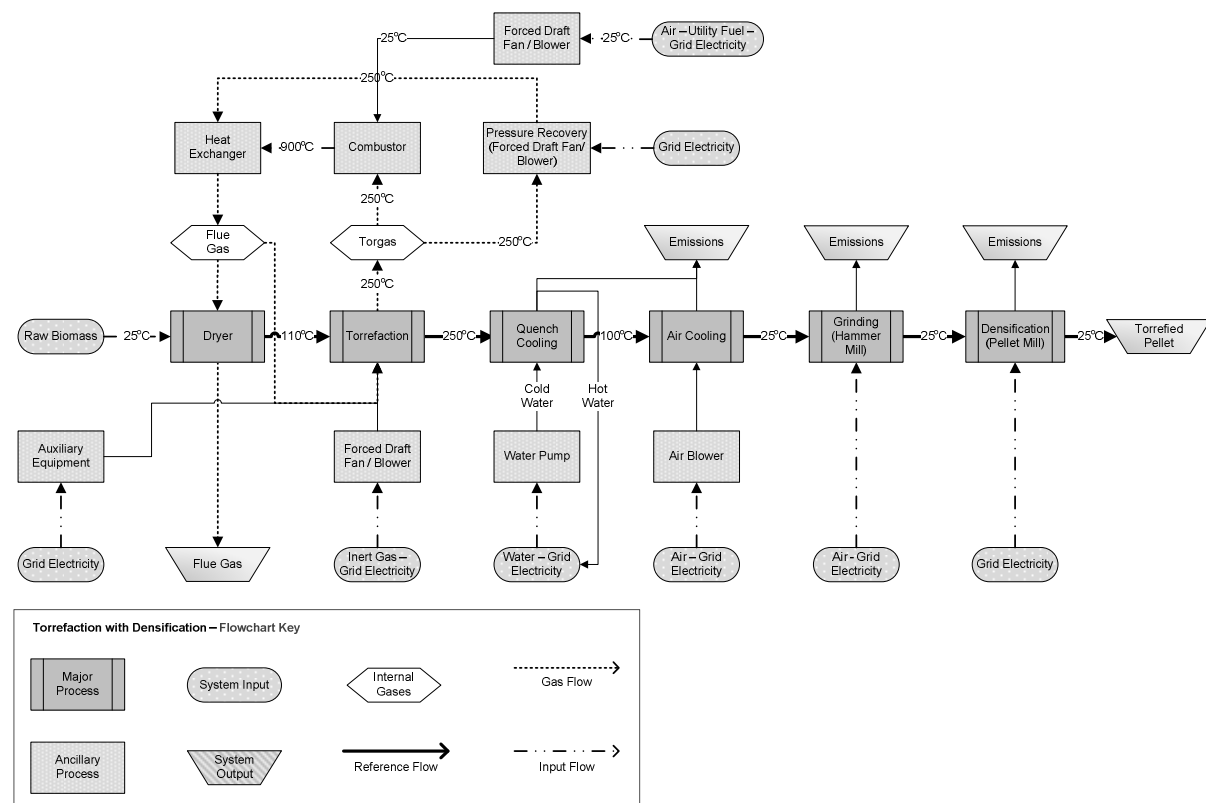


Figure 1: Process flow diagram of the combined torrefaction with densification process

The plant throughput in both the TP/WP cases was assumed as 8.3t/hour based on an annual output capacity of 60kton and 7,200 hours operation per year. 60kton/year was chosen based on a review of existing facilities average scale [8, 28] and so that this study was comparable with a contemporary techno-economic assessment of torrefaction and pelletisation [4].

Raw biomass (wood) is delivered to the facility (see section 3.2) and requires pre-processing (see section 3.3) and drying (see section 3.4). Torrefaction is assumed to occur at 250°C for 30 minutes as this is considered optimal when producing pellets [29]. A key assumption for torrefaction is that the torgas is recirculated, which reduces the requirement for utility fuel, with torgas availability described and assessed in further detail below (see section 3.4). The energy requirements for the torrefaction process are adapted from a recent study by Batidzirai [28] and assume an EU electricity mix, where applicable [33]. No mass losses are assumed to occur in the post processing stages, therefore 0.12 hours of cooling, hammermill, and pelleting unit processes are required to produce 1t of TP/WP (see sections 3.5 & 3.6).

As this is a new technology yet to be commercially demonstrated there is insufficient knowledge or information available about its maintenance and end of life. Consequently, plant replacement, dismantling and disposal are considered outside the scope of the LCA.

### **3.2. Biomass growth, harvesting and transport**

Scots Pine was chosen as a suitable biomass feedstock for this study because of its availability for a European energy market and for the relatively high calorific value of TP manufactured from pine feedstock [30]. Figure 1 is representative of the torrefaction of woody biomass, which typically enters the plant at a MC of 35-40%. Forestry biomass has a MC of 50-60% when harvested [31], hence an initial natural drying in the forest and/or at the facility storage is assumed. The feedstock also requires a pre-drying operation before torrefaction as shown in Figures 1 & 2.

Pine feedstock is assumed to be delivered from a purpose grown and agriculturally managed supply with the same agro-chemical inputs and emissions as those from short rotation forestry (SRF) [32]. Diesel and fertilisers consumed in the cultivation and harvesting processes are modelled using data from ecoinvent [22], DEFRA [33] and IPCC [34]. Annual yields per hectare were assumed to be 14.3t of logs and an additional 2.9t of forest residues [35, 36]. Felling for 1t of scots pine tree would yield 0.8t of pine logs and 0.2t of forest residues with allocation of impacts for this process split 80% and 20% respectively on a mass basis [37].

Transportation of logs from the source of cultivation to the torrefaction plant assumes a density of scots pine of 510kg/m<sup>3</sup>, whilst transportation of forest residues occurs after wood chipping in the forest with an average wood chip density of 295 kg/m<sup>3</sup> [38]. With a circular growth area the transport distance between the site of cultivation and the processing plant is 5.5km for TP and 4.6km for WP assuming maximum distance at the circumference of the forestry plot. This is a conservative value to take account of tortuosity factors. Using scaling factors to account for different densities gives equivalent values of 5.5tkm for pine logs and 9.4tkm for forest residue chips in the TP case with 4.6tkm and 7.8tkm for the WP case.

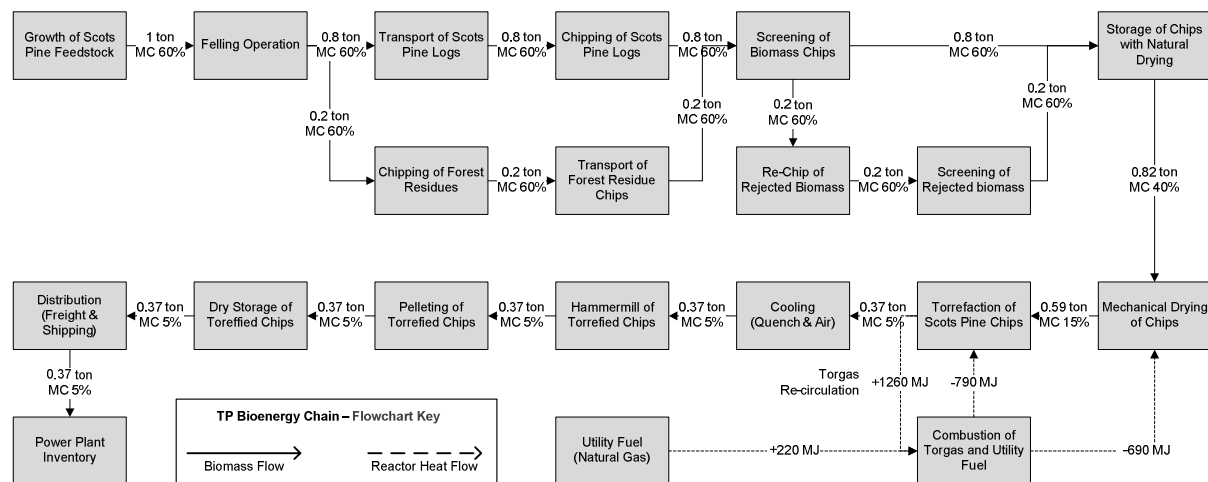


### 3.3. Pre-processing (chipping & screening)

Forest residues chipping occurs at the harvest site prior to transportation using a mobile diesel Heizohack HM 5-400 unit chipper [39] with fuel consumption of 5.49 litres/hour [40]. Chipping of Scots Pine logs occurs at the site of the torrefaction plant prior to storage. Due to the higher volume of logs delivered compared to forest residues, a larger diesel Heizohack HM 14-800 chipping unit was selected to represent this operation [39] with fuel consumption of 13.44 litres/hour [41]. Wood chips are produced to CEN TC/335 P45 specifications by which 80% of chips would be within the range of 3.15-45mm with the remaining 20% assumed to be oversized, requiring a second chipping [42]. To achieve a highly consistent sized feedstock necessary for the torrefaction reactor it is assumed that chips from logs and forestry residues would be passed through a mechanical screening process from a Machinex Disc Screener unit run from EU grid electricity [43]. A screening process was not included in the WP chain since wood chip size distribution was not considered critical for the chip drying operation (see Figure 4).

### 3.4. Torrefaction processing

Figure 2 displays the system diagram that is representative of torrefaction of woody biomass requiring a pre-drying operation before torrefaction. There is uncertainty relating to the quantity of energy required to dry the biomass feedstock prior to torrefaction with values ranging from 2.9-9.0MJ/kg water removed [8, 44]. This variance was accounted for by assuming a base case of 3.0MJ/kg water removed, with a mid case of 6.0MJ/kg and a high case of 9.0MJ/kg assessed in sensitivity case A.



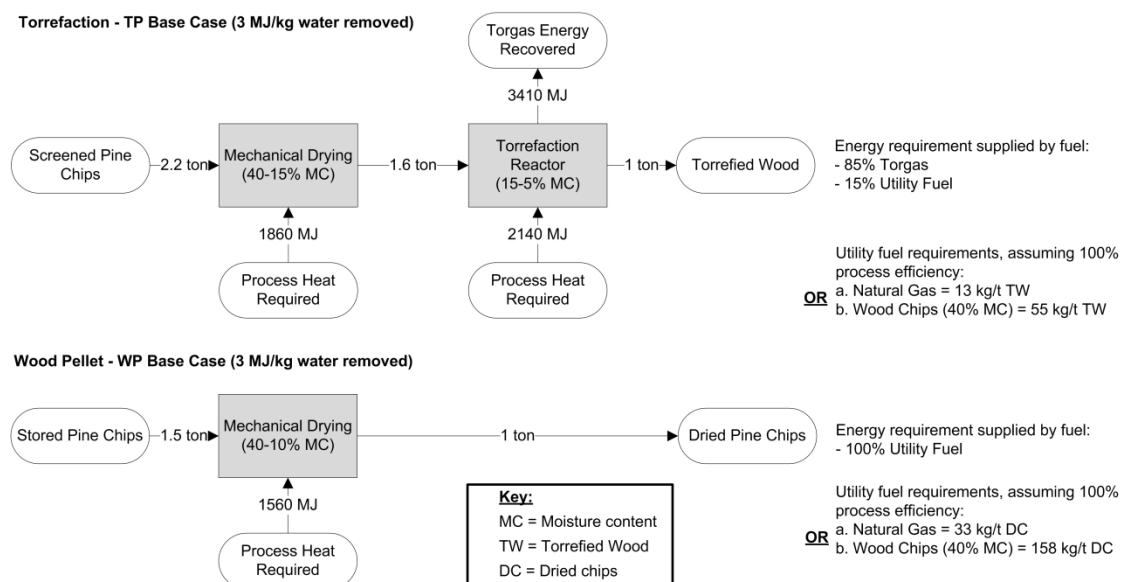
**Figure 2: Torrefaction and pellet plant integrated into the bioenergy process chain**

Mass and energy balances for both WP and TP were developed based on previous research [14, 28, 44]. Figure 2 shows that the MC and mass reduces through the process chain, corresponding to an increase in the energy density and calorific value of the bioenergy fuel. Mass losses are assumed to occur in the drying and torrefaction stages but not in post processing stages. Process heat requirements for drying are estimated using fresh and dry biomass densities before and after natural drying [45].

Torgas is re-circulated through the system and combusted together with makeup utility fuel in a combustion unit. Drying requirements for the TP/WP plant were considered to occur at 100%

process efficiency with the heat supplied from combustion of torgas and natural gas utility fuel for the TP plant and from natural gas only in the WP case. Natural gas was assumed to be delivered to the site of use through a pipeline, with a lower calorific value of 47.14MJ/kg and density of 0.9kg/m<sup>3</sup> [46]. For the torrefaction base case, the torgas was presumed to have a lower calorific value (CV) of 5.70MJ/kg which represented that of Eucalyptus woody biomass in a demonstration unit [28]. The effect of the CV of the torgas on the environmental impact of the TP process is investigated further in the sensitivity analysis and discussion. Emissions from combustion of the torgas from Scots Pine were assumed similar to those of Southern Pine from a previous study, which supposed that limited natural gas utility fuel was required during operation of the TP plant [14]. Emissions from the combustion of natural gas utility fuel were modelled analogously to combustion in a modulating condensing boiler unit [22].

The proportion of energy supplied from the torgas and utility fuel in the TP plant is based on the system flow chart shown in Figure 2 for the base case of 3.0MJ/kg water removed. In this case, 85% of required energy was derived from combustion of the torgas with the remaining 15% supplied from natural gas (see Figure 3). Emissions from the combustion process were scaled according to these figures, with this process described further in the supplementary data.



**Figure 3: Modelled Heat requirements for Torrefied Wood (TW) and Dried Chips (DC) per ton output (assuming 3.0MJ/kg of water removed, 100% combustion efficiency and no system losses)**

Figure 3 shows the mass reduction from drying, the process heat required, and the torgas energy recovered. It also displays the utility fuel necessary to supply the total process heat using natural gas assuming 100% combustion efficiency and no system losses. Approximate values for wood chips (40% MC) are also provided to indicate the relative demand if biomass is used as the utility fuel. This data is provided in Table 2 along with the mid and high cases for drying energy (sensitivity case A). It can be seen that the proportion of the total heat supplied by torgas was reduced as the drying requirement increased. It is also clear that the torrefaction plant required a greater total quantity of heat energy to produce 1t of output compared to the WP plant due to the additional torrefaction reaction process.

**Table 2: Heat energy requirements and utility fuel supply per ton of torrefied wood for TP and per ton of dried pine chips for WP**

	Unit	Torrefied Pellets (TP)			Wood Pellets (WP)		
Output		1 ton of torrefied wood			1 ton of dried pine chips		
Drying energy case (sensitivity case A)	MJ/kg of water removed	3.0	6.0	9.0	3.0	6.0	9.0
Total energy required	MJ	4,000	7,970	12,000	1,560	3,110	4,670
Mechanical drying	MJ	1,860	3,730	5,590	1,560	3,110	4,670
Torrefaction Reactor	MJ	2,140	4,240	6,410	-	-	-
Utility fuel supply <sup>i</sup>							
Natural gas	kg/t (output)	13	96	182	33	66	99
Wood chips (40% MC)	kg/t (output)	55	413	785	142	283	425
Relative contribution							
Utility fuel	%	15	57	72	100	100	100
Torgas	%	85	43	28	n/a	n/a	n/a
i. Assumes lower CV of 47.14MJ/kg for natural gas, and 11.0MJ/kg for wood chips (40% MC)							

In order to operate efficiently, the torrefaction reaction must occur in a low oxygen environment. To represent this, an input of inert gas supply was included in the process flow chain as shown in Figure 1, which assumes that exhaust gases are recirculated with a very low oxygen content to perform this function [47].

Data from the torrefaction of Southern Pine were used to model torgas composition and flue-gas emissions [14, 28]. The ‘auxiliary equipment’ ancillary process in Figure 1 represents the energy requirement of all other equipment and systems, such as control equipment, conveyors and safety circuits, not covered by the remaining major processes [28].

### 3.5. Cooling

After torrefaction, the processed pine chips are cooled to 25°C as shown in Figure 1. The cooling process is included in order to prevent combustion between the torrefied wood and atmospheric oxygen during subsequent processing operations [8]. This can occur at the elevated temperatures of 250°C at which torrefied wood leaves the reactor [9, 48]. Figure 1 shows that cooling is typically performed in two stages, initial quench cooling using water and a secondary air cooling in order to reduce the torrefied wood temperature from 250°C to 25°C. Due to a lack of data available on the cooling process, it was assumed that cooling occurred in one operation with a corresponding EU grid electricity input for the entire process [14, 28]. Water use and emissions to waste water used for cooling were considered outside the scope of this study.

### 3.6. Grinding (Hammermill) & Densification (Pelleting)

Once cooled the torrefied wood next enters a hammermill to be ground in order to reduce particle size before it can be pelleted using a pellet mill [49]. Both the hammermill and industrial pellet mill processes were assumed to be driven using grid electricity delivered to the TP/WP plant using an EU electricity mix. Grinding energy requirement for scots pine torrefied at 250°C is 77kWh/t torrefied

wood (TW) [28] and pelleting energy is 150kWh/t TW [8]. Post treatment grinding energy and pelleting energy requirements of the TP process compared to WP are assessed in sensitivity cases B & C respectively.

### 3.7. Plant infrastructure

Plant infrastructure was considered and included using simplified assumptions based on previous research. Only major items of equipment were included and inventory was limited to the major materials: concrete, steel and aluminium. Material requirements for both 60kton p.a. TP and WP plants were scaled from data for a 290kton p.a. plant using forest residues as a feedstock [11]. This included the dryer, torrefaction reactor, cooling, hammermill, pellet mill and all ancillary equipment in the plant such as conveyors, feeders and control units. Other minor items were left outside of the system boundary.

### 3.8. Distribution & Logistics

It is assumed that pine would be grown in Lillehammer, Norway for use in a coal/biomass co-fired power station in Didcot, UK. The pine would be harvested and processed to TP/WP on site and be transported by road (~450km) to the port of Bergen, Norway. The TP/WP would be transported by an oceanic freight ship (~646nm) to Felixstowe, UK from where it would be distributed by road (~250km) to the power station inventory gate at Didcot. It was approximated that the average transport bulk density of TP/WP would be 800kgm<sup>-3</sup> and 650kgm<sup>-3</sup> respectively as shown in Table 1. Sensitivity case D investigates the implications of growth in Eastern Canada to assess the logistical implications further.

### 3.9. Wood pellet production

Figure 4 illustrates the different system definition and modelling assumptions for conventional wood pellets (WP). Further comparison of key modelling data is provided in Table 3. It is apparent that reduced biomass and land are required for WP, and whilst process heat requirements are low the utility fuel required is higher. Grinding energy is assumed as 260kWh/t based on a study which suggests that energy is approximately 30% of that of un-torrefied biomass [50]. Pelleting energy requirement for dried scots pine is assumed to be 50kWh/t [8]. Electricity is assumed to be supplied from the EU average grid mix [33].

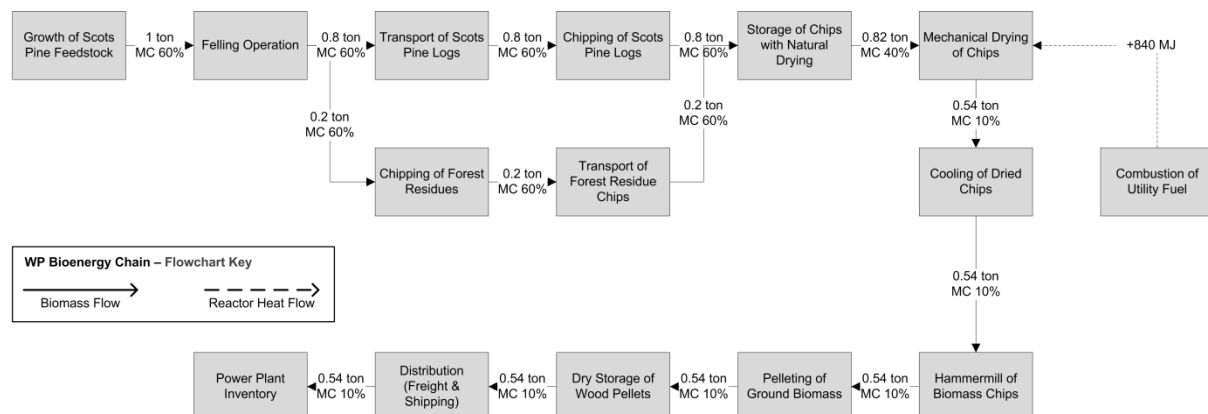


Figure 4: Wood pellet plant integrated into the bioenergy chain

### 3.10. Summary of Key Modelling Assumptions

Table 3 provides a summary of the main differences in the TP and WP system modelling. Several aspects such as cultivation methods, yields, and distance to end user are the same for both systems and are therefore not included here.

**Table 3: Key modelling assumptions for TP and WP systems producing 60kton/a**

	<b>Torrefied Pellets (TP)</b>	<b>Wood Pellets (WP)</b>
<b>Biomass type</b>	Scots Pine	Scots Pine
<b>Biomass volume</b>	163 kton/yr	112 kton/yr
<b>Land area</b>	95 km <sup>2</sup>	66 km <sup>2</sup>
<b>Transport distance to plant</b>	5.5 km	4.6 km
<b>Process heat requirement</b>	4,000 MJ <sub>th</sub> /t of TW	1,560 MJ <sub>th</sub> /t of DC
<b>Natural gas (utility fuel)</b>	14.5 m <sup>3</sup> /t of TW	36.7 m <sup>3</sup> /t of DC
<b>Grinding electricity</b>	77 kWh <sub>e</sub> /t of TW	260 kWh <sub>e</sub> /t of DC
<b>Pelleting electricity</b>	150 kWh <sub>e</sub> /t of TW	50 kWh <sub>e</sub> /t of DC
<b>Transport bulk density</b>	800 kg/m <sup>3</sup>	650 kg/m <sup>3</sup>
<b>Lower Calorific Value</b>	22.0 MJ/kg of TP	15.5 MJ/kg of WP
<b>Moisture content (MC) (wt.%)</b>	5%	10%
Key: TW = Torrefied wood, DC = Dried chips, TP = Torrefied pellets, WP = Wood pellets		

## 4. Results

Results of the LCA study for the modelled TP/WP bioenergy chains are presented in this section, with more detailed findings included in the supplementary data. The functional unit used is the delivery of 1t of TP/WP to the site of use (Didcot, UK). Where appropriate, results have been scaled to the impacts for 1MJ of energy delivered in order to demonstrate the improved energy density of TP.

Normalised endpoint results were evaluated first to identify the environmental issues of importance, these impact categories were then assessed using ReCiPe midpoint. The subsequent sub-sections display the characterised results for individual impact categories. Results for the sensitivity analysis cases A-D (as outlined in section 1.2) are summarised in section 5.

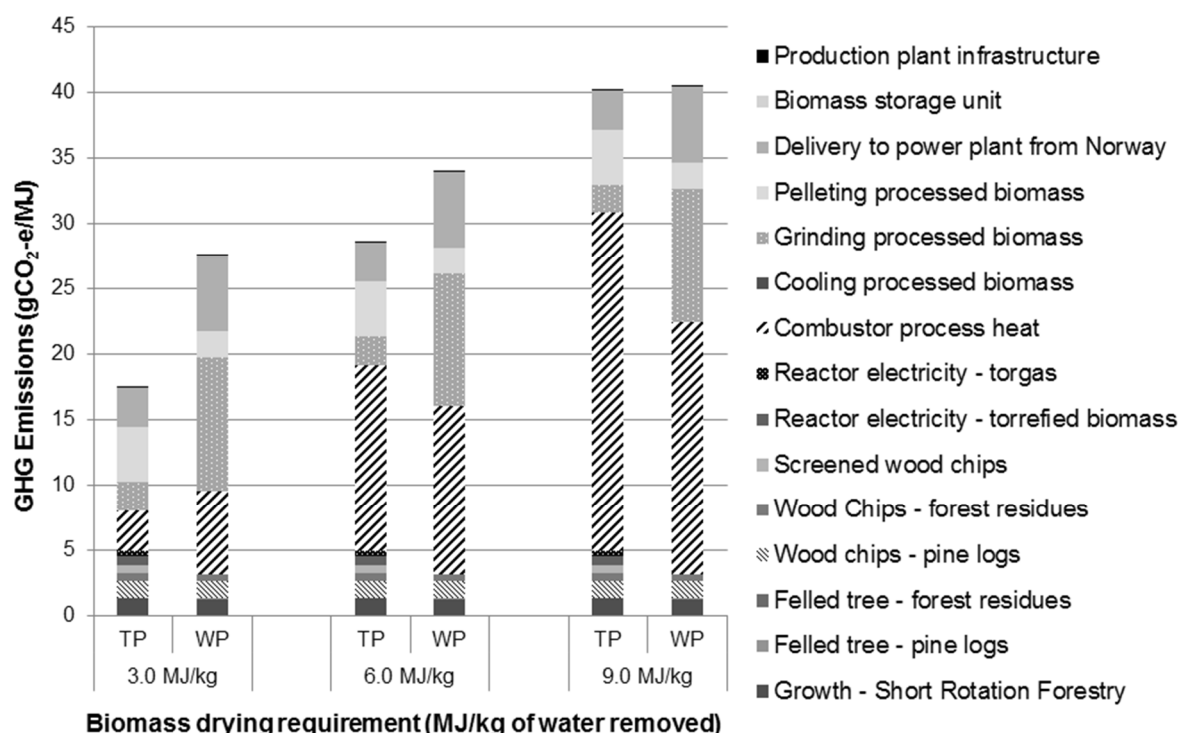
### 4.1. Normalised endpoint results

Normalised results are used in LCA to identify the environmental issues of most importance. Whilst there is uncertainty with normalisation it is a useful process for selecting impact categories for further investigation. Using ReCiPe (endpoint) five categories were found to have substantial impacts, these were climate change (human health), climate change (ecosystems), particulate matter formation, land use, and fossil depletion, which is consistent with previous bioenergy LCAs, e.g. [6, 20]. Other impacts were found to be immaterial and are therefore excluded from further analysis. Normalised results followed similar trends for both TP and WP (see supplementary data).

### 4.2. Climate change (CO<sub>2</sub>e)

Although there are two impact categories at the endpoint in ReCiPe for climate change, there is only one at the midpoint measured in kg of CO<sub>2</sub>e. Due to the uncertainty around energy requirements for biomass drying the results displayed in Figure 5 include sensitivity case A, i.e. the base case

(3.0MJ/kg water removed), mid case (6.0MJ/kg water removed) and high case (9.0MJ/kg of water removed).



**Figure 5: Climate change impacts (gCO<sub>2</sub>e per MJ) delivered of TP/WP bioenergy chains for varying biomass drying requirements (ReCiPe midpoint [H] v1.01)**

Figure 5 shows the principle processes which contribute toward the total greenhouse gas (GHG) emissions are combustor process heat, grinding, pelleting and delivery of products. These results are available in numerical form in Table S6 in the supplementary data. Impacts from the plant and storage infrastructure appear negligible compared against other processes. Results suggest that TP have a lower climate change impact than WP on a MJ delivered basis. The impact contribution from the combustion process is shown to increase significantly for increased drying rates. The reduced climate change impact for TP is more pronounced for the lower drying requirement of 3.0MJ/kg with values of 17.5gCO<sub>2</sub>e/MJ and 27.6gCO<sub>2</sub>e/MJ for the TP/WP cases respectively. Under these conditions, modelled TP offer a 36% improvement per MJ compared to WP. In contrast the high drying case shows very similar total GHG emissions of ~40.5gCO<sub>2</sub>e/MJ.

In all cases GHG emissions for grinding and delivery are higher for the WP case whereas the impacts for pelleting are higher for TP. The combustor heat process is shown to present the dominant impact on climate change for both the mid and high heat requirement cases. For the low drying case of 3.0MJ/kg, Figure 5 shows that pelleting is the dominant contributor for the TP case with the grinding process shown to be the highest for WP. Although the total heat requirement for the low drying TP case is greater than for WP, the impact allocated to the combustion process is lower due to the assumption that 85% of this requirement is provided by the re-circulated torgas (see Figure 3).

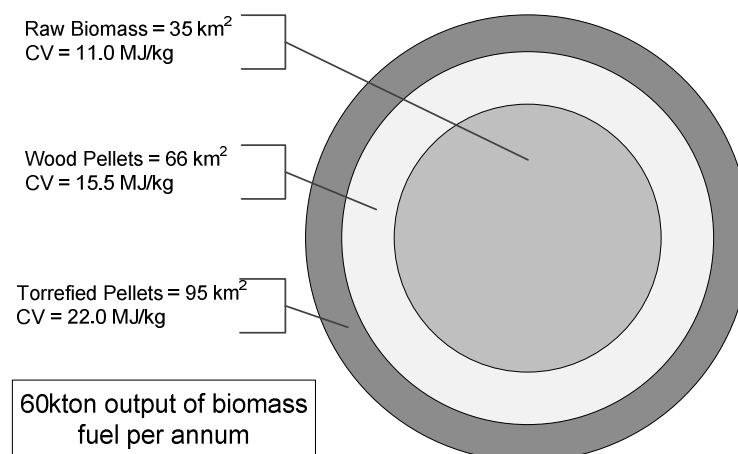
### 4.3. Particulate matter formation (PM10e)

Particulate matter formation (PMF) represents a complex mixture of organic and inorganic substances. Inhalation of diverse particle sizes can cause different human health issues. The particulate impacts for the base case TP/WP chains were calculated as 0.0706gPM10/MJ for TP and 0.0794gPM10/MJ for WP. Both results were found to be dominated by the biomass growth and pre-processing with this accounting for 66% and 58% for the TP/WP base cases respectively. The dominant source of particulates arose from emissions to air from fertiliser application, and the use of diesel in the harvesting and chipping operations. Other significant processes include the delivery to end user, pelleting, grinding, and combustion for process heat.

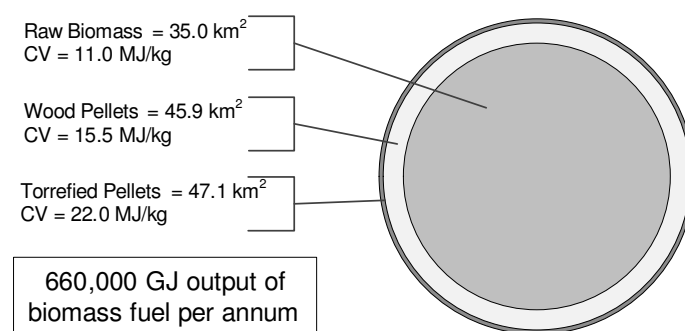
The main source of particulates arises from the use of energy consumed through combustion which is assessed below. Since particulate impacts are dominated by biomass growth, the modelled effects on this impact category were not considered for subsequent sensitivity cases as the biomass growth process is the same for both WP and TP. Additionally, there is a direct relationship between the amount of fuels combusted in the supply chain with the total PMF, hence the assumptions around fuel and energy use are assessed further.

### 4.4. Land use

A relative comparison of the land requirements to produce 60kton output p.a. of raw biomass (wood chips), WP and TP is shown in Figure 6. It can be seen that the land area required to produce TP is significantly greater than for WP due to the reduced mass yield of the TP bioenergy chain as shown in Figures 2 & 3. However the results in Figure 6 assume the same output by mass and not the total energy content of the fuel. If the results are scaled to account for the improved energy density and the equivalent fuel primary energy content of wood chips is used (i.e. 60,000t x 11.0 = 660,000 GJ) we obtain the results portrayed in Figure 7. This assumes that 42,600t of WP and 30,000t of TP are required to provide 660,000 GJ of primary energy in the fuel.



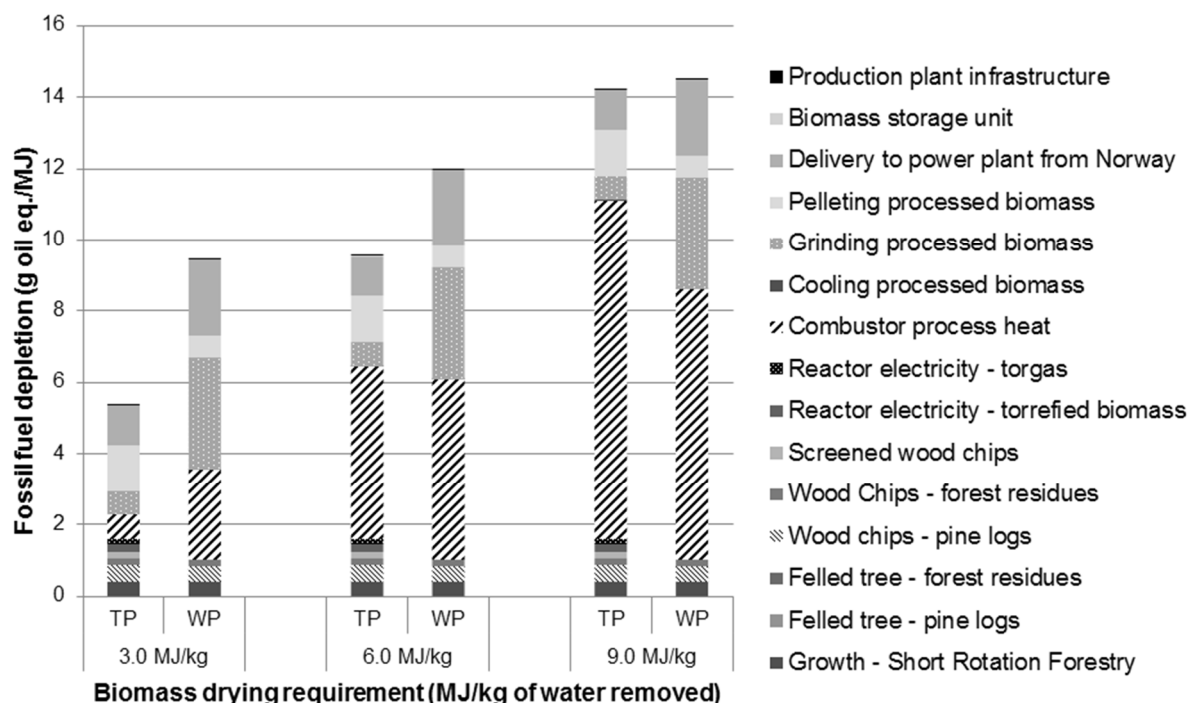
**Figure 6: Relative scale of forestry land occupation for different biomass options on a mass output basis of 60kton/annum**



**Figure 7: Relative scale of forestry land occupation for different biomass options on an energy output (CV) basis of 660,000GJ/annum**

#### 4.5. Fossil fuel depletion

Fossil fuel depletion impacts attributed to the TP/WP chains are shown in Figure 8 for varying biomass drying requirements, on a MJ delivered basis. These results are available in numerical form in Table S7 in the supplementary data. Results show a strong resemblance to the climate change impacts plotted in Figure 5 which suggests that GHG emissions are dominated by the combustion of fossil fuels in the TP/WP production chains. For base conditions, the impacts of fossil fuel depletion are modelled as 43% lower for TP compared to WP with related figures of 20% and 2% for the mid and high drying cases respectively. Similar to the results of Figure 5, the impact benefits for TP fossil fuel depletion are shown to be more pronounced for the lower drying requirement case since the torgas contributes a higher proportion of the total heat requirement as shown.



**Figure 8 – fossil depletion impacts (g oil eq. per MJ delivered) of TP/WP bioenergy chains for varying biomass drying requirements (ReCiPe midpoint [H] v1.01)**

A point to note for fossil fuel depletion (and climate change) are the relative contribution of combustor process heat for each of the three sensitivity A cases: for the 3.0MJ/kg low case WP has



about 3 times the depletion of TP, for 6.0MJ/kg mid case TP and WP are similar, whereas the 9.0MJ/kg high case shows combustor process heat is higher for TP.

#### 4.6. Net energy analysis

A cumulative energy demand (CED) comparison of the TP/WP chains was investigated to represent the sum of all primary energy required to deliver 1kg of TP/WP to the end-user [21, 23]. Net energy analysis is used as a proxy for resource depletion, and for both the TP/WP chains the proportion of primary energy supplied by non-renewable sources was over 98% therefore the values are calculated for non-renewable energy only.

Results for CED show the relative impacts follow comparable contributions as those displayed in Figure 8 (fossil fuel depletion). Table 4 summarises the results for each drying case for CED, Energy Gain Ratio (EGR), and Energy Requirement for Energy (ERE) which are metrics used to assess energy technologies [20]. The EGR is defined as the primary energy available from a system over its lifetime (measured by CV) divided by the life cycle primary energy input (measured as CED). ERE is the inverse of EGR and represents how much primary energy input is required to deliver 1 MJ of fuel.

**Table 4: Net energy analysis results (CED, EGR & ERE) for TP and WP under different drying energy scenarios**

	Torrefied Pellets (TP)			Wood Pellets (WP)		
Drying energy case [sensitivity case A] (MJ/kg of water removed)	3.0	6.0	9.0	3.0	6.0	9.0
Cumulative Energy Demand (CED) (MJ/kg)	5.78	9.63	13.96	7.08	8.75	10.41
Energy Gain Ratio (EGR) (MJ <sub>delivered</sub> /MJ <sub>primary</sub> )	3.81	2.28	1.58	2.19	1.77	1.49
Energy Requirement for Energy (ERE) (MJ <sub>primary</sub> /MJ <sub>delivered</sub> )	0.26	0.44	0.63	0.46	0.56	0.67

A positive (>1) value for EGR is possible for renewable energy sources, with higher ratios representing improved processing energy efficiency. TP results show that the low case has more than twice the EGR than the high case due to the lower combustion heat requirements. The CED low case per kg of modelled TP is 18% lower than for the equivalent WP case, with the ERE for TP is 43% lower than the WP case. For the high case, the EGR and ERE results are comparable for TP and WP and demonstrates that 0.63 – 0.67 MJ of non-renewable energy are required for every 1 MJ of delivered fuel. This shows that where high amounts of drying are required the EGR isn't favourable.

#### 5. Sensitivity Analysis

Sensitivity analysis focused on fossil fuel depletion (FFD) and climate change (CC) as land use is not affected by the sensitivities, and particulate matter formation (PMF) impacts were dominated by biomass cultivation with the data used in this category being more uncertain. Summary results for the sensitivity analyses are presented in Table 5.

### **5.1. Case A – Drying energy and CV of torgas**

Results in Section 4 show that the relative proportion of the total TP process heat requirement able to be supplied by torgas has a significant influence on the climate change and fossil depletion impacts. Sensitivity case A assessed different drying energy requirement to remove 1kg water from biomass (3.0, 6.0 and 9.0 MJ/kg removed). As these results were displayed in sections 4.2, 4.5 & 4.6 the drying sensitivity is not further analysed here.

In addition to drying, the calorific value (CV) of torgas and the ability to utilise the heat integration has a strong effect on the end results. A review of literature revealed different CVs assumed for torgas with the re-circulated fuel strongly dependant on the biochemical composition and MC of the biomass feedstock. Three separate torgas CVs were investigated for this sensitivity: 5.70MJ/kg for Eucalyptus (15% MC) base case [28], 2.65MJ/kg for Willow (14.4% MC) low case [51], 6.13MJ/kg for Larch (9.8% MC) high case [51]. Evidently, the high case shows reduced impacts for TP.

Taking the low case, the torgas available is 46.5% of the base case which reduces the torgas heat recovered to 1,600MJ per ton of TW, providing only 40% of the process heat. This increases the natural gas utility fuel requirement to 51kg/t of TW (60% process heat) for 3.0MJ/kg drying, and 245kg/t of TW (87% process heat) for 9.0MJ/kg drying. TP still comes out better compared to WP in terms of CC and FFD under the low drying energy scenario, but worse than WP in the high scenario. This illustrates the importance of using the torgas and how sensitive results are to assumptions around its CV.

### **5.2. Case B – Grinding (hammermill) energy**

Sensitivity case B assessed the post treatment grinding energy requirements of the TP process compared to WP. Literature suggests that grinding energy for torrefied wood (TW) varies depending on the condition of reaction and biomass feedstock [28]. Laboratory based studies also suggest that the grinding energy is related to the relative anhydrous mass loss during torrefaction with the greatest reduction in energy observed for reactions involving a high mass loss [50]. The degree of anhydrous mass loss is dependent on the feedstock, reactor conditions and reactor design [52].

Base case grinding energy assumed that scots pine torrefied at 250°C requires 77kWh/t of TW [28] compared with 260kWh/t of DC in WP production, this being 333% of the TW value [50]. A sensitivity case assuming that grinding energy is the same as WP was considered, i.e. no improvement in grinding through torrefaction. The sensitivity showed that grinding energy for TP accounts for 31-32% of the CC (22.5gCO<sub>2</sub>e/MJ) and FFD (6.9g oil eq./MJ) impacts. Under these conditions, TP show higher overall CC and FFD results compared to WP for the high drying energy scenario (see Table 5).

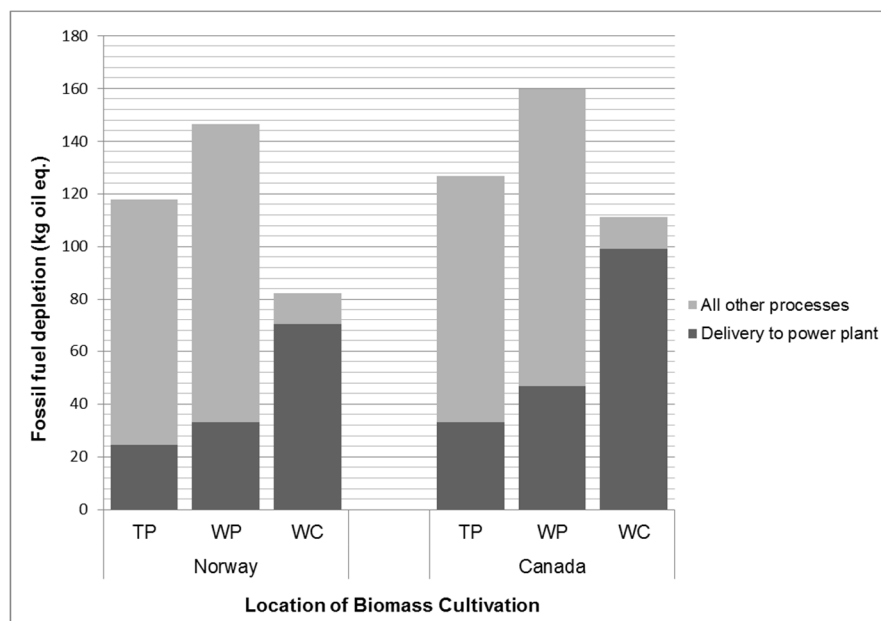
### **5.3. Case C – Pelleting energy**

Energy requirements for the pelleting of torrefied wood (TW) was investigated as sensitivity case C. Similar to the grinding sensitivity, the pelleting energy requirements for torrefied wood are believed to be dependent on the torrefaction reaction conditions and biomass feedstock [28, 49]. From a previous study of pellet processing it was found that energy relates to the biochemical composition of the TW product with significantly higher pelleting energy requirements observed for torrefaction reactions above 250°C, in which a greater degree of devolatilisation was shown to occur [49].

Three cases for the required pelleting energy of TW were chosen to represent the best and worst cases suggested in torrefaction literature. A worst case pelleting energy requirement of 300% compared to the un-torrefied case was considered [8]. Some sources suggest that pelleting energy is reduced by torrefaction so a case of 50% compared to un-torrefied biomass was also included [4]. For comparison, an unrepresentative case of 100% was modelled to demonstrate the difference in the total impacts of TP/WP if pelleting energy requirements were the same for both cases. This sensitivity showed that for TP the CC and FFD impacts are lower than WP, regardless of the pelleting energy requirement modelled in each case (see Table 5).

#### 5.4. Case D – Biomass location and logistics

Location of the biomass and subsequent supply chain logistics were assessed in sensitivity case D. As high volumes of wood pellets are shipped from North America into Europe [3, 6], this sensitivity considered biomass cultivation in Nova Scotia, Canada for high case transportation with transport distances of 650km road and 5,860km sea approximated for this case. Results showed that the increased impacts of TP were less than the increase for WP confirming that longer journeys are more beneficial for TP (see Table 5). As an additional case, wood chips were assessed to illustrate the relative impacts of pre-processing compared to transportation for FFD base case (see Figure 9).



**Figure 9: Sensitivity case C results for TP, WP and Wood Chips (WC) produced in Norway and Canada comparing fossil fuel depletion for transportation with all other processes**

#### 5.5. Sensitivity Analysis – Summary Results

Table 5 provides a summary of results for sensitivity cases A-D:

**Table 5: Sensitivity Analysis Summary Results for FFD and CC**

Sensitivity Case			Climate Change (g CO <sub>2</sub> e/MJ)			Fossil Fuel Depletion (g oil eq./MJ)		
			3.0	6.0	9.0	3.0	6.0	9.0
A	Torrefied Pellets (TP)	TP	17.5	28.6	40.3	5.4	9.5	14.2
	Wood Pellets (WP)	WP	27.5	34.0	40.5	9.4	12.0	14.5
B	Grinding energy = WP	TP	22.5	33.6	45.3	6.9	11.0	15.7
C	Pelleting energy = 300% of WP	TP	17.5	28.6	40.3	5.4	9.5	14.2
	Pelleting energy = 100% of WP	TP	14.7	25.8	37.5	4.5	8.6	13.3
	Pelleting energy = 50% of WP	TP	14.0	25.1	36.8	4.3	8.4	13.1
D	Biomass supply from Canada	TP	18.5	29.6	41.3	5.8	9.9	14.6
	Biomass supply from Canada	WP	30.2	36.7	43.2	10.3	12.9	15.4

## 6. Discussion

Results presented in sections 4 & 5 were based on the system description and modelling assumptions described in section 3 and are sensitive to the energy required for drying, grinding, and pelleting, and the availability of torgas to reduce utility fuel demand in the torrefaction process. This section discusses the key findings and assumptions and provides additional context to the study.

### 6.1. Land Use

Land use is a key issue as it shows torrefaction requires more land to produce a given output. As land is a limited resource this could restrict the implementation of torrefaction unless end-users are willing to pay a premium for an improved product. Figure 6 displayed that almost 3 times more land is required for TP than wood chips, and ~50% more than WP, for a given mass output. When the energy output is considered, TP requires only slightly more land than WP, but both require approximately one third more land than wood chips (see Figure 7). The amount of land required would increase further if the utility fuel was biomass rather than the natural gas assumed in this study (see section 6.3). This raises the question about whether pre-processing biomass into pellets is necessary. The answer depends on the location of the biomass in relation to final use (see section 6.5), and the end use application, i.e. pellets have different uses to wood chips.

Land use change (LUC) is outside the scope of this paper, but is nonetheless a critical issue for bioenergy systems [53]. Biodiversity loss and greenhouse gas emissions from LUC must be accounted for therefore additional land occupation should balance against competing land uses to optimise efficient use of a limited resource [54, 55]. As TP uses more land, the economics determine if this is desirable, but the impact on ecosystem services also defines whether this is justified.

### 6.2. Biomass supply, cultivation & harvesting

Whilst the use of roundwood and sawlogs may not be a realistic option economically due to competing industries offering high prices than bioenergy [56], this study is focused on the comparison of the technology and overall supply chain, therefore biomass feedstock is not a key concern. It is acknowledged that short rotation forestry (SRF) may not be the most representative

proxy measure as emissions from cultivation vary considerably [32, 54]. However this is immaterial here as both TP and WP systems use the same feedstock so the primary focus is gate-to-gate.

Results show that biomass supply is not the most important life cycle stage for fossil fuel depletion or GHG emissions, but it could be a key consideration if carbon stocks were affected [54] or if biomass was more energy intensive to produce. Land use (see section 6.1) is a serious factor when deciding on which biomass feedstock to use.

This study assumes that torrefaction technology is limited to primarily woody biomass as the MC, bulk density and particle size distribution of the feed system needs to be accurately controlled [8]. Agricultural biomass tends to ignite or carbonize easily during torrefaction, and also has relatively low bulk density which means the volume of feed streams required is higher [17]. Waste feedstocks are not usually desirable for utilities due to unfavourable chemical composition having a negative impact on performance and stricter emission limits [8, 17], although they are more desirable due to their lower value [13]. Perhaps most importantly woody biomass is usually available throughout the year whereas other feedstock streams often have limited or seasonal variability [5]. Nevertheless, significant research is under way to explore the potential agricultural residues as this feedstock is plentiful and could become a worthwhile torrefaction feedstock in the long term [8].

Emissions to air from cultivation were shown to contribute significantly to particulate matter formation. This is due primarily to the use of fertiliser and the assumptions around  $N_2O$  from soil, in addition to diesel combusted in forestry operations. Using forest residues would reduce this impact but it should also be noted that forestry systems have much lower inputs than agriculture [32].

### **6.3. Torrefaction process, torgas availability & utility fuel**

Results revealed that where low drying energy is required TP have lower impacts than WP, whereas for high drying energy the two systems are comparable on a per MJ delivered basis. A key assumption is that torgas can significantly reduce the need for utility fuel. If torgas is not available or the CV is lower than assumed then the benefit of torrefaction is more questionable and impacts are likely to be more than WP. The effect of biomass composition on the gravimetric make-up of the process torgas was not considered in this study. Some studies have suggested that all of the torrefaction process heat could be provided from torgas in order to achieve auto-thermal operation. However some utility fuel will always be required in order to provide the necessary start up energy to reach this condition, irrespective of the overall process efficiency [13-15].

Another supposition is that natural gas is used for utility fuel. Results from Figure 8 suggest that natural gas usage in the reactor combustion process provides the greatest scope for reducing the overall fossil depletion impacts for the TP. If biomass were to be used instead this would make WP more favourable for the mid and high drying energy scenarios. Table 2 estimated that if biomass was used for utility fuel then for TP high drying energy would require an additional 868kg of biomass per ton of torrefied wood, compared to an additional 472kg per ton of dried wood chips. This clearly places additional demands on land use meaning that one ton of TP would require more than 3.5 tonnes of biomass to produce. A compromise is therefore required between whether natural gas or biomass is used for process heat with the trade-off between non-renewable resource, climate impacts, and land occupation considered.

#### **6.4. Post torrefaction processes – cooling, grinding & pelleting**

Sensitivity case B assessed the assumptions on grinding energy. The majority of literature sources suggest that grinding energy reductions of 70-90% occur for TW which suggests that the 30% case modelled provides a more realistic representation of the process [5, 8, 9, 50]. This reduction is achievable through the breakdown of the fibrous hemicellulose/lignin structure during torrefaction [9]. Greater reductions in grinding energy requirements are achieved when a greater percentage of hemicellulose is removed from the biomass, often attributed to more severe reaction conditions [50]. Although beneficial from a grinding energy perspective, the degree of biomass devolatilisation determines the mass-yield of torrefaction. Reduced grinding energy requirements should be considered against the economic and delivered product energy potential impacts of the TP fuel for a process involving a lower mass-yield [52].

Pelleting energy requirements were assessed in sensitivity case C. It is suggested that the increased energy needed for TW occurs through the breakdown of organic hemicellulose through the torrefaction process. Hemicellulose acts as a natural lubricant during pelleting, a reduction in the TW hemicellulose fraction therefore causes an increase in friction between the biomass and the press-die walls of the pellet mill [49]. The amount of pelleting energy for TW is expected to rise with increased hemicellulose devolatilisation at more extreme reaction conditions. The mechanical strength and durability of the pellet is also an important factor with studies suggesting that lignin acts as a natural binding agent within TP/WP [17]. Studies have shown that pellet strength and durability greatly decrease for torrefaction temperatures over 250°C [49] due to the onset of lignin degradation at higher process temperatures [9]. The addition of a biological additive to the pelleting stage to replace the lignin component from torrefaction may ensure that TP maintain the mechanical durability of WP alternatives [17].

Data on water use in the cooling operations were not available and were therefore omitted from the study. Studies suggest that un-pelleted TW offers a risk of self-heating and un-controlled combustion when stored due to its high carbon content and dust formation characteristics [8, 28, 48]. Cooling and densification are therefore crucial stages, with transportation also requiring a dense product. Further assessment of cooling operations is recommended for future research.

After torrefaction biomass demonstrates hydrophobic characteristics making outdoor storage more attractive and less susceptible to biological degradation [5]. There are uncertainties about the benefits in storage due to limited long-term studies [8], end-user confidence around storage behaviour and health & safety requires demonstration [6].

#### **6.5. Distribution & Logistics**

In all scenarios and sensitivities, TP are shown to offer improvements in supply chain logistics due to the improved bulk density that is of benefit when transport is volume limited. The increase in CV also provides an advantage when transport is weight restricted. It is clear that reductions in fossil fuel use and GHG savings are achieved where complex logistics or long distances are required [4]. Torrefaction is of limited benefit when the end-user is located close to the biomass source as the energy and emissions from pre-processing outweigh the savings in distribution (see Figure 9).

## 6.6. Validity and limitations of results

This study was limited to modelling the TP/WP processes using general plant operating data published in literature. Process requirements and data for commercial demonstration units are likely to be different to the values used to produce the system models, contributing to limitations in the results. A lack of published commercial data for torrefaction has been cited previously for causing a significant gap in the general understanding of the technology [11, 44]. Nonetheless, the knowledge of torrefaction is improving with related studies to this work producing analogous results, although Agar *et. al* do not account for torgas [57].

Modelling assumptions described in section 3 are essential in LCA but results need to consider these in context. It is important to note the suppositions made on the comparative heat energy of the TP/WP processes [28], the parasitic electricity requirements [13], and the infrastructure requirements of the TP/WP facilities [11]. To provide a fair comparison these modelling assumptions were kept the same for both cases to offer less uncertainty than the quantified values so the assumptions for both technologies remained consistent.

Critical to the modelling of the TP/WP chains was an appreciation of the mass yield of biomass from harvest through to delivery to the end-user. These models were based on predicted MC of Scots Pine for each stage which would be different for alternative feedstocks. The model assumed 100% mass efficiency and no product losses throughout the TP/WP bioenergy chains. In reality this assumption is not achievable, with biomass losses in each transport, storage and processing stage expected [32]. Similarly, the assumption of 100% combustion efficiency is not realistic in practice, but is used in this study to allow the reader to use the inventory data for different efficiencies and also to assist in focusing on the comparative LCA by using fewer variables between the two systems.

## 7. Concluding Remarks

This study analysed the potential environmental impacts associated with integrating torrefaction into bioenergy systems to produce torrefied wood pellets (TP). Results were compared with conventional wood pellet (WP) production to assess the comparative impacts. Findings from this study evaluated on a MJ delivered basis show that torrefied pellets (TP) offer reduced fossil fuel consumption and greenhouse gas emissions compared to conventional wood pellets (WP) when low drying energy is assumed, although an increased amount of land is required. Under a high drying energy scenario TP displayed similar results to WP. Data for particulate matter formation were more uncertain but showed similar impacts for both TP and WP.

The torrefaction process is sensitive to both the drying requirements of biomass in the reactor and the proportion of process heat supplied by the re-circulated gases [7, 8]. Relative impact savings of the TP process compared to WP are dependent on the proportion of the total process heat requirement supplied by the re-circulated torgas and the type of utility fuel used.

Increased land use represents a potential barrier to the implementation of torrefaction due to the mass losses in processing. Transportation advantages are achieved with TP over long distances although where high drying energy is required the benefits are marginal overall.

This study demonstrates the theoretical advantages although the torrefaction system does not currently exist on a commercial scale. There are several barriers to be overcome, and TP need to become cost competitive with wood pellets [6, 58]. End-user confidence around combustion properties, grindability, storage behaviour, and health & safety needs to be proven [8]. There are also technical barriers to address including predictability and consistency of product quality, process gas handling and contamination, densification of torrefied biomass, heat integration, and the flexibility in using different input materials [5-9, 17, 28].

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## **References**

1. European Commission. Directive 2009/28/EC of The European Parliament and of The Council of 23 April 2009 on the promotion of the use of energy from renewable sources. Official Journal of the European Union 2009, 16-62, Brussels, 2009.
2. European Commission. A policy framework for climate and energy in the period from 2020 to 2030, CM(2014) 15 final, European Commission, Brussels, 2014.
3. Lamers, P., Junginger, M., Hamelinck, C. & Faaij, A. Developments in international solid biofuel trade. *Renewable and Sustainable Energy Reviews*, 16(5), 2012, 3176-3199. DOI: 10.1016/j.rser.2012.02.027
4. Uslu, A., Faaij, A. & Bergman, P. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. *Energy*, 33(8), 2008, 1206–23. DOI: 10.1016/j.energy.2008.03.007
5. National Non-Food Crops Centre. Techno-Economic Assessment of Biomass Densification Technologies. Project 08-015. York, UK, 2008.
6. Adams, P., Shirley, J., Whittaker, C., Shield, I., Darvell, L., Jones, J. & McManus, M.C. Integrated Assessment of the potential for torrefied wood pellets in the UK electricity market. World Bioenergy 2014 conference, Jönköping, Sweden, 3-5 June, 2014, 235-239.
7. Van der Stelt, M., Gerhauser, H., Kiel, J. & Ptasiński, K. Biomass upgrading by torrefaction for the production of biofuels: A review. *Biomass & Bioenergy*, 35, 2011, 3748-3762. DOI: 10.1016/j.biombioe.2011.06.023
8. Koppejan, J., Sokhansanj, S., Melin, S. & Madrali, S. IEA Bioenergy Task 32 report. Status overview of torrefaction technologies. International Energy Agency (IEA), Enschede, 2012.



9. Tumuluru, J., Sokhansanj, S., Hess, J., Wright, C. & Boardman, R. A review on biomass torrefaction process and product properties for energy applications. *Industrial Biotechnology*, 7 (5), 2011, 384-401. DOI: 10.1089/ind.2011.7.384
10. Chen, S. Life Cycle Assessment of Wood Pellet. MSc thesis, Chalmers University of Technology, Göteborg, Sweden, 2009. Available at: <http://publications.lib.chalmers.se/records/fulltext/141464.pdf> (accessed 18th March 2014)
11. Kabir, M. & Kumar, A. Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. *Bioresource Technology*, 124, 2012, 394–405. DOI: 10.1016/j.biortech.2012.07.106
12. OFGEM. Renewables Obligation: Sustainability Criteria Guidance. Office for Gas & Electricity Markets, London, 2014.
13. Morey, V., Tiffany, D., Kaliyan, N., & Lee, W. Biomass Torrefaction – Understanding Greenhouse Gas Emissions and Potential Financial Opportunities. University of Minnesota Report No. RS-0028-12, Minnesota, 2013.
14. Skone, T. NETL Life Cycle Inventory Data: Short Rotation Woody Crop Biomass Torrefaction. National Energy Technology Laboratory, Pittsburgh, 2012.
15. Bergman, P. Boersma, A., Zwart, R. & Kiel, J. Torrefaction for biomass co-firing in existing coal-fired power stations “biocoal”. Report ECN-C-05-013. ECN, Petten, The Netherlands, 2005.
16. Kiel, J. Torrefaction for biomass upgrading into commodity fuels. Proceedings of the IEA Bioenergy Task 32 Workshop on Fuel Storage, Handling and Preparation and System Analysis for Biomass Combustion Technologies, Berlin, Germany, 2007.
17. Kleinschmidt, C. Overview of international developments on torrefaction. Central European Biomass Conference 2011, Graz, Austria, January 26–28, 2011.
18. International Standards Organisation (ISO). Environmental management – life cycle assessment – principles and framework, Second Edition, EN ISO 14040, ISO, Geneva, 2006.
19. International Standards Organisation (ISO), Environmental management – life cycle assessment – requirements and guidelines, Second Edition, EN ISO 14044, ISO, Geneva, 2006.
20. Adams, P. & McManus, M. Small-scale biomass gasification CHP utilisation in industry: Energy and environmental evaluation. *Sustainable Energy Technologies and Assessments*, 6, 2014, 129-140. DOI: 10.1016/j.seta.2014.02.002
21. Pre Consultants. SimaPro life cycle assessment software [v7.3], Pre Consultants, Amersfoort, The Netherlands, 2007.
22. Swiss Centre for Life Cycle Inventories. ecoinvent database [v2.0], EPMA, Switzerland, 2009.
23. Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J. & Van Zelm, R. ReCiPe 2008 – A life cycle impact assessment method which compares harmonised category indicators at the

midpoint and the endpoint level. First edition, Report I: Characterisation. Ministry of Housing, Spatial Planning and Environment (VROM), The Netherlands, 2009.

24. Roberts, F. The aims, methods and uses of energy accounting, *Applied Energy*, 4, 1978, 199-217. DOI: 10.1016/0306-2619(78)90003-X

25. Slessor, M. *Energy in the Economy*, Macmillan Press, London, 1978.

26. Frischknecht R., Jungbluth, N. Althaus H. J., Bauer C., Doka G., Dones R., Hirschler R., Hellweg S., Humbert S., Köllner T., Loerincik Y., Margni M. & Nemecek, T. Implementation of Life Cycle Impact Assessment Methods,ecoinvent report No. 3. Swiss Centre for Life Cycle Inventories, Switzerland, 2007.

27. Acharya, B., Sule, I. & Dutta, A. A review on advances of torrefaction technologies for biomass processing. *Biomass Conversion and Biorefinery*, 2(4), 2012, 349-369. DOI: 10.1007/s13399-012-0058-y

28. Batidzirai, B., Mignot, A., Schakel, W., Junginger, H., Faaij, A. Biomass torrefaction technology: Techno-economic status and future prospects. *Energy*, 62, 2013, 196–214. DOI: 10.1016/j.energy.2013.09.035

29. Stelte, W., Sanadi, A., Shang, L., Holm, J., Ahrenfeldt, J. & Henriksen, U. Recent developments in biomass pelletization – A review. *BioResources*, 7(3), 2012, 4451-4490.

30. Phanphanich, M. & Mani, S. Impact of torrefaction on the grindability and fuel characteristics of forest biomass. *Bioresource Technology*, 102(2), 2011, 1246–53. DOI: 10.1016/j.biortech.2010.08.028

31. ECN. Phyllis – database for the composition of biomass and waste [online]. Energy Research Centre of the Netherlands (ECN). Petten, The Netherlands, 2009. Available at: <http://www.ecn.nl/phyllis/> (Accessed 12<sup>th</sup> March 2014)

32. E4Tech. Solid and Gaseous Biomass Carbon Calculator 1.0. Available at: <https://www.ofgem.gov.uk/publications-and-updates/uk-solid-and-gaseous-biomass-carbon-calculator> (Accessed 15th May 2014)

33. DEFRA. Greenhouse Gas Conversion Factor Repository. HM Stationery Office, London, 2013. Available at: <http://www.ukconversionfactorscarbonsmart.co.uk/> (Accessed 1<sup>st</sup> April 2014)

34. IPCC. Climate Change 2007. IPCC Fourth Assessment Report. The Physical Science Basis, Cambridge, 2007. Available at: <http://www.ipcc.ch/ipccreports/ar4-wg1.htm> (Accessed 20th April 2014)

35. The Macaulay Land Use Research Institute. Agroforestry Toolbox. Aberdeen, Scotland, 2010. Available at: [http://www.macaulay.ac.uk/agfor\\_toolbox/trees.html](http://www.macaulay.ac.uk/agfor_toolbox/trees.html) (Accessed 17th March 2014)

36. Biomass Energy Centre. Potential outputs of biofuels per hectare, per annum. Forest Research, Farnham, UK, 2014. Available at:

[http://www.biomassenergycentre.org.uk/portal/page?\\_pageid=75,163231&\\_dad=portal&\\_schema=PORTAL](http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,163231&_dad=portal&_schema=PORTAL) (Accessed 17th March 2014)

37. Reap, J., Roman, F., Duncan, S. & Bras, B. A survey of unresolved problems in life cycle assessment. *International Journal of Life Cycle Assessment*, 13, 2008, 290-300. DOI: 10.1007/s11367-008-0008-x

38. Aebiom. Wood Fuels Handbook. Legnaro, Italy, 2008. Available at: [http://www.aebiom.org/IMG/pdf/WOOD\\_FUELS\\_HANDBOOK\\_BTC\\_EN.pdf](http://www.aebiom.org/IMG/pdf/WOOD_FUELS_HANDBOOK_BTC_EN.pdf) (Accessed 17th May 2014)

39. Heizohack. Woodchippers. Heizomat Gerätebau- Energiesysteme GmbH, Gunzenhausen, Germany, 2013. Available at: [http://www.deu.heizomat.de/pdfs/Heizohack\\_Holzhackmaschinen\\_ENG.pdf](http://www.deu.heizomat.de/pdfs/Heizohack_Holzhackmaschinen_ENG.pdf) (accessed 31st March 2014)

40. Webster, P. Chipper Review. Project ref: 500S/35/04, Forest Research, Farnham, UK, 2005.

41. Webster, P. Large Chippers. Project ref: 500S/37/06 & FR06054, Forest Research, Farnham, UK, 2007.

42. CEN. TC/335 P45 Biomass Standards. European Committee for Standardization, Brussels, 2014. Available at: <http://standards.cen.eu/> (Accessed 3rd July 2014)

43. Machinex. Disc Screener with Plastic Perforator. Worldwide Recycling Equipment Sales, LLC, 2014. Available at: <http://www.wwrequip.com/equipment/13649.htm> (accessed 31st March 2014)

44. Ciolkosz, D. & Wallace, R. A review of torrefaction for bioenergy feedstock production. *Biofuels Bioproduction Biorefining*, 5(3), 2011, 317–29. DOI: 10.1002/bbb.275

45. Biomass Energy Centre. Typical densities of common woods. Reference Library, Forest Research, Farnham, UK, 2014. Available at: <http://www.biomassenergycentre.org.uk/> (Accessed 17th March 2014)

46. ORNL. Biomass Energy Data Book - Lower and Higher Heating Values of Gas, Liquid and Solid Fuels. Oak Ridge National Laboratory, US Department of Energy, 2011. Available at: <http://cta.ornl.gov/bedb/index.shtml> (Accessed 31st March 2014)

47. Sarvaramini, A. & Larachi, F. Integrated biomass torrefaction – Chemical looping combustion as a method to recover torrefaction volatiles energy. *Fuel*, 116, 2014, 158–67. DOI: 10.1016/j.fuel.2013.07.119

48. Junsatien, W., Soponpongpiat, N. & Phetsong, S. Torrefaction Reactors. *J Sci Technol MSU*, 32 (1), 2013.

49. Stelte, W., Nielsen, N., Hansen, H., Dahl, J., Shang, L. & Sanadi, A. Pelletizing properties of torrefied wheat straw. *Biomass & Bioenergy*, 49, 2013, 214–21. DOI: 10.1016/j.biombioe.2012.12.025

50. Kokko, L., Tolvanen, H., Hämäläinen, K. & Raiko, R. Comparing the energy required for fine grinding torrefied and fast heat treated pine. *Biomass & Bioenergy*. 42, 2012, 219–23. DOI: 10.1016/j.biombioe.2012.03.008
51. Prins, M., Ptasinski, K. & Janssen, F. Torrefaction of wood: Part 2. Analysis of products. *J Anal Appl Pyrolysis*, 77 (1), 2006, 28–34. DOI: 10.1016/j.jaap.2006.01.001
52. Dhungana, A., Basu, P. & Dutta, A. Effects of Reactor Design on the Torrefaction of Biomass. *J Energy Resour Technol*, 134(4), 2012, 041801. DOI:10.1115/1.4007484
53. Berndes, G., Bird, N. & Cowie, A. Bioenergy, Land Use Change and Climate Change Mitigation. IEA Bioenergy Task 39, ExCo:2010:03, 2010. Available at: <http://task39.org/files/2013/05/Bioenergy-Land-Use-Change-and-Climate-Change-Mitigation.pdf> (Accessed 12th July 2014)
54. Adams, P., Gilbert, P., Howard, D., Thornley, P., Whittaker, C., Whitaker, J., et al. Understanding the greenhouse gas balances of bioenergy systems. Supergen Bioenergy Hub, Tyndall Centre for Climate Change Research, University of Manchester, UK, 2013. Available at: <http://www.supergen-bioenergy.net/home/News/2013/09/16/greenhouse%20gas%20report> (Accessed 14th July 2014)
55. Power, A. Ecosystem services and agriculture: tradeoffs and synergies. *Phil. Trans. R. Soc. B*, 365 (1554), 2010, 2959-2971. DOI: 10.1098/rstb.2010.0143
56. Smeets, E.M. & A.C. Faaij., Bioenergy potential from forestry in 2050: an assessment of the drivers that determine the potentials. *Climatic Change* 81(3), 2007, 353-390. DOI: 10.1007/s10584-006-9163-x
57. Agar, D. Gil, J., Sanchez, D., Echeverria, I. & Wihersaari, M. Torrefied versus conventional pellet production - A comparative study on energy and emission balance based on pilot-plant data and EU sustainability criteria, *Applied Energy*, Available online 4 September 2014, ISSN 0306-2619, <http://dx.doi.org/10.1016/j.apenergy.2014.08.017>.
58. Adams, P.W., Hammond, G.P., McManus, M.C. & Mezzullo, W.G. Barriers to and drivers for UK bioenergy development, *Renewable and Sustainable Energy Reviews*, 15, 2011, 1217-1227. DOI: 10.1016/j.rser.2010.09.039